Advanced Review

Instruction and cognition

Jennifer G. Cromley* and James P. Byrnes

When teachers provide instruction to students, they provide opportunities for students to learn information. To be maximally effective, these opportunities should present information in ways that are compatible with the way the mind works. Using a US Department of Education *Practice Guide* as a structure for our review, we review 'second wave' cognitive science research on spaced learning, worked examples, coordinating visual and verbal representations, coordinating and concrete representations, quizzing, delayed Judgment of Learning, and explanatory reasoning. We also contextualize these lines of research within the contemporary K-12 classroom environment and constraints on teachers and school administrators. We close by advocating that all stakeholders in the instructional process also remember 'first wave' cognitive science findings, and also recommend more research on how specific motivational constructs could be brought to bear to encourage students to use these proven but effortful learning principles.

How to cite this article:
WIREs Cogn Sci 2012, 3:545–553. doi: 10.1002/wcs.1192

INTRODUCTION

When teachers provide instruction to students, they provide opportunities for students to learn information. To be maximally effective, these opportunities should present information in ways that are compatible with the way the mind works. Describing how the mind works is the central task of the field of cognitive science. Despite the natural affinity between instructional design and cognitive science, the latter did not have a strong influence on classroom instruction until the 1980s, when lab-based research on constructs such as summarization strategies,[1] schemata,[2,3] and problem-solving heuristics[4,5] were picked up by applied researchers and tested in classrooms. These constructs from cognitive science then reached teachers and influenced their classroom instruction, often via the courses and textbooks for initial (i.e., pre-service) teacher training, in workshops for practicing teachers (i.e., in-service training), and in generalist teacher magazines such as *Phi Delta Kappan* or *American Educator* or via more specialized subject-matter magazines. The process of translating even highly consistent findings from cognitive science into instructional methods that can be robustly applied in instruction is a slow one, even in areas such as reading instruction where such translation is routine. Several reasons have been offered for the slow pace of this translational process: the complexity of classroom environments[6] (where social dynamics, personal attributes, and institutional features are constantly interacting); the difficulty of determining 'what works, for whom, and under what conditions'[7] [Institute for Education Sciences (IES), 2012] when moving from controlled laboratory experiments to dynamic classroom settings (which also means moving from volunteer undergraduates who have self-selected into college to younger students who are obliged to attend school),[6] teachers' tendency to teach the way they were taught,[8] the tendency for teachers to view cognitive science research as less scientific or useful than so-called 'brain research',[9] and disincentives for scholars to engage in the work of 'translation'.[10]

To give one example, cognitive models of human memory would seem to have simple applications to classroom instruction. Information needs to enter the sensory register, then a working memory system, and finally be encoded into long-term memory. Teachers should use encoding techniques to build students' knowledge. However, classrooms typically include upwards of 20 students, each of whom has stored in memory his or her own knowledge about the

---

*Correspondence to: jennifer.Cromley@temple.edu

Department of Psychological Studies in Education, Temple University, Philadelphia, PA, USA

topic, including misconceptions not known by the teacher, or in some cases idiosyncratic conceptions. A teacher who wishes to understand what students know must deal with constraints of time (schools now face many more demands on their time from non-academic activities, test preparation, and testing itself), student engagement (e.g., a high proportion of non-college bound students still required to attend high school, students more distracted by electronic devices during school time), and required curriculum pacing guides. To move laboratory research on memory to the classroom, therefore, researchers must be sensitive to these time and curriculum constraints and variability in student characteristics. In addition, these principles might be 'translated' via how a teacher delivers a lesson, how a textbook is structured, and/or via a computer-based system such as an intelligent tutor. Consider how difficult it would be for a physician to translate information from anatomy and biology texts directly into knowledge of how to treat patients.

A second generation of instructional methods based on cognitive science is now ready for classroom use, perhaps best summarized by the US Department of Education's IES in a 2007 Practice Guide entitled *Organizing Instruction and Study to Improve Student Learning*.[11] This practice guide presents seven principles with strong-to-low levels of evidence for effectiveness: (1) space learning over time, (2) interleave worked example solutions and problem-solving exercises, (3) combine graphics with verbal descriptions, (4) connect and integrate abstract and concrete representations of concepts, (5) use quizzing to promote learning, (6) help students allocate study time efficiently, and (7) help students build explanations by asking and answering deep questions. Below, we review the evidence on which these seven principles were originally based and add more recently published evidence.

RECOMMENDATION 1: SPACE LEARNING OVER TIME

The typical instructional approach suggested by textbooks and pacing guides is to cover a topic, assign, and provide feedback on homework and/or tests about that topic, and move on to the next chapter and topic. Robust findings from more than 100 years of research since Ebbinghaus[12] on spaced learning suggest that frequently revisiting topics improve retention. However, 85% of the studies on spaced learning have been conducted with undergraduate samples.[13] A few recent studies have focused on classrooms with school-aged children,[14,15] in early childhood,[16] with longer retention intervals,[17] and the optimal amount of spacing relative to the time point of testing.[18] Cepeda and colleagues[13] identified a ratio of test delay-to-interstimulus interval that was optimal for retention; this curvilinear relationship suggests that longer test delays require longer interstimulus interval to produce optimal learning. So instead of encountering the material once for a unit and again for a final exam, students would be more likely to retain material long term if they, for example, encountered the material in brief reviews on a monthly basis. All of the cited studies continue to find a robust effect of spacing. There are several prominent explanations for the effectiveness of spacing, including improved procedural knowledge[19] and interference with forgetting.[18]

RECOMMENDATION 2: INTERLEAVE WORKED EXAMPLE SOLUTIONS AND PROBLEM-SOLVING EXERCISES

While textbooks often present solutions, there is a robust literature showing that worked examples showing every step of the solution process are associated with better learning (Figure 1; note that not all worked examples include visual representations, and not all traditional solutions omit visual representations).

Only a small subset of learners can without guidance identify the appropriate procedure, identify the relevant and irrelevant information, and perform correct calculations or apply appropriate inductive or deductive reasoning. The majority of learners benefits from explicit demonstrations of these steps, as shown in research with middle school,[20,21] high school,[22–24] and undergraduate[25] students across

Question: How many linear feet of fencing is needed to enclose an area $6' \times 10'$?

Traditional solution: 32 ft. or Perimeter $= 2W + 2L = 32$ ft.

Worked example: Perimeter $= 2W + 2L$; $W = 6$, $L = 10$; $2(6) + 2(10) = 32$ ft.
Alternative solution: Perimeter $= W + L + W + L$; $W = 6$, $L = 10$; $6 + 10 + 6 + 10 = 32$ ft.

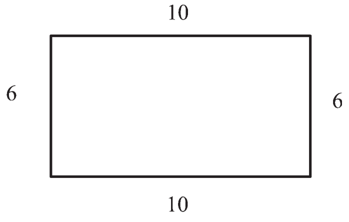

FIGURE 1 | Sample worked example.

multiple academic domains such as chemistry,[25] geometry,[20] and algebra.[24] Furthermore, worked examples can be effective in both individual and small group settings.[20] Learners also benefit from having opportunities to practice problem solving very soon after seeing worked examples.[26,27] However, learners may need a critical level of prior knowledge before they can benefit from worked examples,[25] and presenting worked examples in multiple steps and with strategy prompts can lead to better learning.[21] Worked examples have been under-researched in domains outside of science, technology, engineering, and mathematics (STEM), perhaps because STEM problems tend to be well-defined and many are solvable using specific heuristics. In addition, only about 25% of worked example studies have been conducted with school-aged children.

RECOMMENDATION 3: COMBINE GRAPHICS WITH VERBAL DESCRIPTIONS

Like undergraduate textbooks, K-12 textbooks in science, mathematics, history/social studies, and other subjects routinely combine text with graphics such as photographs, line diagrams, tables, graphs, and hybrids of these representations.[28] Despite the aphorism that ‘a picture is worth a thousand words’, there are four robust research findings that most instructors are not aware of: (1) experts but not novices know what to pay attention to in the graphics—they know what the main point of the graphic is and know how to use graphic conventions such as captions to identify the main point,[29] (2) most learners skip most representations,[30–32] (3) when learners do look at the representations they do not look at the representations in depth,[33] and (4) when learners do look at representations in depth—either spontaneously[30] or when trained[34,35]—they learn more from the representations. Despite the popular belief among teachers that learner preferences or ‘styles’ should drive the way materials are presented, there is growing evidence that learner preference is irrelevant but learners’ skills (e.g., spatial ability[36]) do play a role, especially in learning from text without diagrams. Instructors at all levels can directly instruct students in how to combine the verbal information and the discipline-specific graphics they are expected to use in their own learning.[37] Instructors should also be attentive to the possibility that a visual representation can create or reinforce a misconception,[38] although there has been little systematic psychologically based research on principles for avoiding such pitfalls.

RECOMMENDATION 4: CONNECT AND INTEGRATE ABSTRACT AND CONCRETE REPRESENTATIONS OF CONCEPTS

Abstract concepts such as democracy, fractions, and molecular reactions are often taught using some concrete representation such as a physical model used in hands-on science learning, films, role plays, visuals, or realia used to teach vocabulary and story comprehension to young children.[39–41] Across a wide range of ages, domains, and skills, the literature supports a balance between concrete representations to help students build understanding and abstract representations to promote transfer. Concrete examples can enable high-quality reasoning[42] but are simultaneously associated with overly narrow application—learners may take less-central aspects of a concrete example to be central to the principle being instructed.[43–45] For example, children who solve a word problem involving chairs that uses proportional reasoning can come to believe that all problems involving chairs also use proportional reasoning.[46] Likewise, physics students who learn about refraction from an example using a rectangular prism show a bias toward the surface pattern of the light ray (bending downwards on entry and then bending upwards on exiting to parallel the angle of entry) when solving a problem with a triangular prism.[47]

At the same time, abstract principles are more difficult to reason with, and until they build up a body of concrete examples, learners may not form a deep understanding of the abstract principle.[48] The combination of abstract and concrete, together with explicit links between each concrete example and the abstract principle which it instantiates, can lead to optimal learning.[49] In some circumstances, however, the linking of abstract to concrete can hinder learning—algebra students given function problems with objects that had the same beginning letter as the symbol in the function (e.g., a for apple) showed worse performance than abstract symbols not linked to concrete objects.[50]

RECOMMENDATION 5: USE QUIZZING TO PROMOTE LEARNING

The research evidence for quizzing or other delayed retrieval methods as a way to promote learning is stronger now than when quizzing studies were reviewed for IES (see Refs 51 and 52 for recent reviews). Frequent quizzes are associated with better achievement in middle school history,[53] middle school science,[54] introductory psychology,[55] undergraduate statistics,[56] and non-verbal tasks such as map learning.[57] Delayed retrieval—i.e., attempting after a delay of typically 1 day to 1 week to recall what was learned—has been found to be more effective than other re-study methods.[58]

In addition to better learning, testing is associated with transfer of skills to uninstructed content.[53,59,60] Furthermore, despite learners' beliefs that easy learning is a sign of high-quality learning, the *desirable difficulties* hypothesis is supported by a number of studies with middle school[61] and undergraduate[62] students. Correct retrieval when retrieval is effortful is associated with better memory for studied content.[62,63] Finally, while testing without feedback is effective, the addition of feedback makes testing even more effective.[64]

A secondary principle from the IES *Practice Guide* is preinstructional quizzes or preinstructional questioning as a means to improve learning. Preinstructional questions appear to activate prior knowledge, encourage students to monitor their level of knowledge, and spark curiosity thereby increasing student effort. The literature on this principle has likewise grown: the prequestioning effect appears to hold with middle school[65,66] and high school[66] students learning science.[65,66] In addition, recent studies with undergraduates continue to support the effectiveness of preinstructional quizzes or preinstructional questioning.[67–70] These quizzes can also serve as a type of formative assessment teachers can use to adjust their teaching and students can use to adjust their studying and recalibrate their level of understanding.

RECOMMENDATION 6: HELP STUDENTS ALLOCATE STUDY TIME EFFICIENTLY

The *Practice Guide* suggested two principles: (1) teach students how to use *delayed* Judgment of Learning (JOL) to prioritize material for additional studying and (2) give students the opportunity to find out what they need to study by providing feedback on tests and quizzes. JOL pertains to a self-assessment of how well one understands or 'knows' some material, and the delayed JOL principle refers to performing such a self-assessment following a delay of typically 1 h to 1 day, rather than immediately after a learning trial. A recent meta-analysis of the delayed JOL principle[71] shows that it is robust with children, college-aged, and older samples; the effect size for immediate versus delayed JOL is smaller ($g = 0.48$) with children than with college-aged adults ($g = 0.96$). The *delayed* JOL principle contrasts with many students' study habit of checking their level of understanding *immediately* after learning (e.g., reading, studying, hearing a lecture). The illusion of knowing is common immediately after learning but is much reduced after a delay.[72] Students who think they know material well when they do not, will not study as much or as hard as they should. Recent research suggests that scaffolding in the form of hints during retrieval trials can lead to better retrieval at delayed test.[73]

Feedback is routinely provided by instructors on test and quizzes, but learners may not construe this as information to inform their further study; learners can be fixated on the performance aspect of feedback and ignore the information aspect of feedback. Motivational research on students' mastery goal orientation versus performance goal orientation is informative on this phenomenon.[74] Learners who see the goal of learning as understanding (mastery goal orientation) tend to use more adaptive study practices than learners who see the goal of learning as either showing high performance (performance-approach goal orientation) or avoiding low performance (performance-avoid goal orientation). Teachers can lower the weight of quizzes to overall grades and give messages that explicitly connect their feedback with the need to re-study certain topics and thereby shift learners' perceptions of assessments as predominantly summative to a more formative view of the purposes of assessment. Little classroom-based research exists on either the delayed JOL principle or the informative feedback principle.

RECOMMENDATION 7: HELP STUDENTS BUILD EXPLANATIONS BY ASKING AND ANSWERING DEEP QUESTIONS

Classroom discussion questions, end-of-chapter questions, or homework that ask students to explain *why* an event happened or why a phenomenon occurs can help build an integrated, principled understanding. Unfortunately, most instructional materials focus on literal questions such as 'how many members of Congress does each state have in the House of Representatives and the Senate'? and only a minority of questions in traditional school curricula require explanations, such as 'Why are there different numbers of representatives per state in the House of Representatives and the Senate'? Students benefit from teachers (or software 'agents', e.g., Ref 75) modeling explanatory reasoning. Self-explanation is one particular approach to fostering explanatory reasoning: it is a multifaceted activity that includes gap-filling inferences, bridging inferences, knowledge elaboration, metacognitive monitoring, and fix-up strategies.[76] Self-explanations can be spontaneous[77,78] or prompted by instruction.[75,79,80] Self-explanation has been studied with many different tasks, such as diagram comprehension,[79] map reading,[81] math,[82] reading comprehension of scientific text,[83] statistics,[84] and with participants across a wide range of ages.[85] In addition to effects on instructed material, self-explanation frequently shows transfer effects.[86] While the vast majority of self-explanation studies have been conducted with individual students who verbalize their solo self-explanations, Hausmann and colleagues[87] found that learners in an undergraduate physics course gained more from an explanation intervention when working in dyads compared to learning from solo self-explanation.

Without prompting to explain, learners may fail to detect patterns in material they are studying.[88] On the other hand, self-explanation produces the greatest benefits on measures of deep conceptual understanding and can lead to less practice in procedures and therefore lower scores on procedural tasks.[89] In addition, without scaffolding, self-explanation can put a heavy load on working memory, rendering the technique ineffective.[90,91] Teachers and school systems may justifiably choose to use explanation-based methods to build deep understanding and simultaneously also use 'first generation' cognitive principles (e.g., mnemonics, rhyming, speeded practice) to build fluency in procedural skills and/or to build up the basic knowledge base that allows for high-level reasoning.

FIRST WAVE COGNITIVE SCIENCE PRINCIPLES AND MOTIVATION

Beyond these 'second wave' cognitive science principles, we feel it is important to not ignore either 'first wave' principles (e.g., mnemonics) or student motivation (e.g., self-efficacy) in instruction. The IES *Practice Guide* focuses on a small set of principles to build deep, conceptual knowledge through high-level reasoning. Teachers and school administrators may need to be reminded that in order to reason, students need some knowledge (including vocabulary knowledge) to reason with.[49] Well-validated 'first wave' cognitive science principles—such as activating prior knowledge, strategy instruction, teaching vocabulary, the efficiency of using direct instruction in some circumstances, and using memory devices to teach the small amount of information that must be memorized—should not be neglected. In addition, the principles in the *Practice Guide* for the most part require more effort on the part of students, and learner motivation may play a larger role with this sort of instruction. Current research in academic achievement motivation treats motivation as a multifaceted and domain-specific construct, with active research on how motivation affects effortful strategy use and reasoning by measuring constructs such as self-efficacy,[92] epistemological beliefs[93] (beliefs about whether learning is simple and straightforward or complex, as well as other beliefs about the nature of knowledge), emotions,[94] students' beliefs about the purposes of learning[95] (to understand versus to obtain high scores or grades: goal orientation), student perceptions of the value or relevance of various topics,[96] and the motivating power of offering choices[97] (self-determination theory). Research on these motivational variables in the context of spacing, worked examples, coordinating visual and verbal representations, coordinating abstract and concrete representations, quizzing (especially in the current high stakes testing environment[98]), delayed JOL, feedback, and explanatory reasoning may help these useful techniques reach more students in more classrooms. In addition, there are a variety of findings and theoretical approaches within specific domains (e.g., math learning, science learning, etc.) that can provide additional guidance as to (1) what to expect when teaching students of particular ages and (2) how to design instruction to be more effective that is also thoroughly grounded in the science of mind (see reviews such as Ref 99). In the area of mathematics learning, for example, researchers have made a distinction between procedural knowledge (knowing how to perform certain computations or algorithms) and conceptual knowledge (understanding why these computations must be performed in a specific way and the meaning of symbols). Many studies have shown that children who have more conceptual knowledge (e.g., of fractions) learn procedures more readily and remember these procedures better.[100]

ACKNOWLEDGMENTS

The writing of this article was supported by a sabbatical leave awarded to JGC in Spring 2012 by Temple University. We thank Julie L. Booth for comments on an earlier version of this article.

REFERENCES

1. Brown AL, Day JD. Macrorules for summarizing texts: the development of expertise. *J Verbal Learn Verbal Behav* 1983, 22:1–14.
2. Bransford JD, Johnson M. Considerations of some problems of comprehension. In: Chase WG, ed. *Visual Information Processing*. New York: Academic Press; 1973, 383–438.
3. Hinsley D, Hayes JR, Simon HA. From words to equations: Meaning and representation in algebra word problems. In: Carpenter PA, Just MA, eds. *Cognitive Processes in Comprehension*. Hillsdale, NJ: Erlbaum; 1978, 89–106.
4. Rimm-Kaufman SE, Hamre BK. The role of psychological and developmental science in efforts to improve teacher quality. *Teach Coll Rec* 2010, 112: 2988–3023.
5. Brown JS, Burton RR. Diagnostic models for procedural bugs in basic mathematical skills. *Cogn Sci* 1978, 2:155–192.
6. Hulleman CS, Cordray DS. Moving from the lab to the field: the role of fidelity and achieved relative intervention strength. *J Res Educ Eff* 2009, 2:88–110.
7. Available at: http://nces.ed.gov/programs/slds/other.asp. (Accessed February 13, 2012).
8. Kagan DM. Professional growth among preservice and beginning teachers. *Rev Educ Res* 1992, 62:129–169.
9. Alferink LA, Farmer-Dougan V. Brain-(not) based education: dangers of misunderstanding and misapplication of neuroscience research. *Exceptionality* 2010, 18:42–52.
10. Feldman A. Does academic culture support translational research? *CTS* 2008, 1:87–88.
11. Pashler H, Bain P, Bottge B, Graesser A, Koedinger K, McDaniel M, Metcalfe J. *Organizing Instruction and Study to Improve Student Learning*. Washington, DC: National Center for Education Research, Institute of Education Sciences, Department of Education (US); 2007,63 p. Report No. NCER 2007–2004.
12. Ebbinghaus H. *Memory: A Contribution to Experimental Psychology*. New York: Teachers College Columbia University; 1913 (Original work published 1885).
13. Cepeda NJ, Pashler H, Vul E, Wixted JT, Rohrer D. Distributed practice in verbal recall tasks: a review and quantitative synthesis. *Psychol Bull* 2006, 132:354–380.
14. Nakata T. English vocabulary learning with word lists word cards and computers: implications from cognitive psychology research for optimal spaced learning. *ReCALL* 2008, 20:2–30.
15. Sobel HS, Cepeda NJ, Kapler IV. Spacing effects in real-world classroom vocabulary learning. *Appl Cogn Psychol* 2011, 25:763–767.
16. Vlach HA, Ankowski AA, Sandhofer CM. At the same time or apart in time? The role of presentation timing and retrieval dynamics in generalization. *J Exp Psychol Learn Mem Cogn* 2012, 38:246–254.
17. Cepeda NJ, Vul E, Rohrer D, Wixted JT, Pashler H. Spacing effects in learning: a temporal ridgeline of optimal retention. *Psychol Sci* 2008, 19:1095–1102.
18. Storm BC, Bjork RA, Storm JC. Optimizing retrieval as a learning event: when and why expanding retrieval practice enhances long-term retention. *Mem Cogn* 2010, 38:244–253.
19. Taylor K, Rohrer D. The effects of interleaved practice. *Appl Cogn Psychol* 2010, 24:837–848.
20. Retnowati E, Ayres PL, Sweller J. Worked example effects in individual and group work settings. *Educ Psychol* 2010, 30:349–367. doi: 10.1080/01443411003659960.
21. Schmidt-Weigand F, Hänze M, Wodzinski R. Complex problem solving and worked examples. *Z Padagog Psychol* 2009, 23:129–138.
22. Hilbert TS, Renkl A, Kessler S, Reiss K. Learning to prove in geometry: learning from heuristic examples and how it can be supported. *Learn Instr* 2008, 18:54–65.
23. Renkl A, Atkinson RK, Maier UH, Staley R. From example study to problem solving: smooth transitions help learning. *J Exp Educ* 2002, 70:293–315.
24. Salden RJCM, Aleven VAWMM, Renkl A, Schwonke R. Worked examples and tutored problem solving: redundant or synergistic forms of support? *Top Cogn Sci* 2009, 1:203–213. doi: 10.1111/j.1756-8765.2008.01011.x.
25. Darabi AA, Nelson DW, Palanki S. Acquisition of troubleshooting skills in a computer simulation: worked example vs. conventional problem solving instructional strategies. *Comput Hum Behav* 2007, 23:1809–1819.
26. Sweller J, Cooper GA. The use of worked examples as a substitute for problem solving in learning algebra. *Cogn Instr* 1985, 2: 59–89. doi: 10.1207/s1532690xci0201_3.
27. Trafton JG, Reiser BJ. The contributions of studying examples and solving problems to skill acquisition. In: Polson M, ed. *Proceedings of the Fifteenth Annual Conference of the Cognitive Science Society*. Hillsdale, NJ: Erlbaum; 1993,1017–1022.
28. McTigue EM, Croix A. Illustration inquiry: visual literacy in science. *Sci Scope* 2010, 33:17–22.
29. Kozma R, Russell J. Multimedia and understanding: expert and novice responses to different representations of chemical phenomena. *J Res Sci Teach* 1997, 43:949–968.
30. Hannus M, Hyönä J. Utilization of illustrations during learning of science textbook passages among low- and

high-ability children. *Contemp Educ Psychol* 1999, 24:95–123.

31. Schmidt-Weigand F, Kohnert A, Glowalla U. A closer look at split visual attention in system- and self-paced instruction in multimedia learning. *Learn Instr* 2010, 20:100–110. doi: 10.1016/j.learninstruc.2009.02.011.
32. Schwonke R, Berthold K, Renkl A. How multiple external representations are used and how they can be made more useful. *Appl Cogn Psychol* 2009, 23:1227–1243. doi: 10.1002/acp.1526.
33. Cromley JG, Snyder-Hogan LE, Luciw-Dubas UA. Cognitive activities in complex science text and diagrams. *Contemp Educ Psychol* 2010, 35:59–74. doi: 10.1016/j.cedpsych.2009.10.002.
34. Berthold K, Renkl A. Instructional aids to support a conceptual understanding of multiple representations. *J Educ Psychol* 2009, 101:70–87.
35. Bodemer D, Faust U. External and mental referencing of multiple representations. *Comput Hum Behav* 2006, 22:27–42.
36. Kolloffel B. Exploring the relation between visualizer-verbalizer cognitive styles and performance with visual or verbal learning material. *Comput Educ* 2012, 58:697–706.
37. Cromley JG, Bergey BW, Fitzhugh SL, Newcombe N, Wills TW, Shipley TF, Tanaka JC. Effectiveness of student-constructed diagrams and self-explanation instruction. Manuscript under review.
38. Muthukrishna N, Carnine D, Grossen B, Miller S. Children's alternative frameworks: should they be directly addressed in science instruction? *J Res Sci Teach* 1993, 30:233–248.
39. Marley SC, Levin JR, Glenberg AM. Improving Native American children's listening comprehension through concrete representations. *Contemp Educ Psychol* 2007, 32:537–550.
40. Rubman CN, Waters HS. A B seeing: the role of constructive processes in children's comprehension monitoring. *J Educ Psychol* 2000, 92:503–514.
41. Wasik BA, Bond MA, Hindman AH. The effects of a language and literacy intervention on Head Start children and teachers. *J Educ Psychol* 2006, 98:63–74.
42. Griggs RA, Cox JR. The elusive thematic-materials effect in Wason's selection task. *Br J Psychol* 1982, 73:407–420.
43. De Bock D, Deprez J, Van Dooren W, Roelens M, Verschaffel L. Abstract or concrete examples in learning mathematics? A replication and elaboration of Kaminski Sloutsky and Heckler's study. *J Res Math Educ* 2011, 42:109–126.
44. Kaminski JA, Sloutsky VM, Heckler AF. The advantage of abstract examples in learning math. *Science* 2008, 320:454–455.
45. Schwartz DL, Chase CC, Oppezzo MA, Chin DB. Practicing versus inventing with contrasting cases: the effects of telling first on learning and transfer. *J Educ Psychol* 2011, 103:759–775. doi: 10.1037/a0025140.
46. Van Dooren W, De Bock D, Hessels A, Janssens D, Verschaffel L. Not everything is proportional: effects of age and problem type on propensities for overgeneralization. *Cogn Instr* 2005, 23:57–86.
47. Brookes DT, Ross BH, Mestre JP. Specificity, transfer, and the development of expertise *Phys Rev Spec Top Phys Educ Res* 2011, 7:010105.
48. Moreno R, Ozogul G, Reisslein M. Pre-college electrical engineering teaching with concrete and abstract visual representations: effects on students' problem solving problem representations and learning perceptions. *J Educ Psychol* 2011, 103:32–47.
49. Schwartz DL, Bransford JD. A time for telling. *Cogn Instr* 1998, 16:475–522.
50. McNeil NM, Weinberg A, Hattikudur S, Stephens AC, Asquith P, Knuth EJ, Alibali MW. A is for apple: mnemonic symbols hinder the interpretation of algebraic expressions. *J Educ Psychol* 2010, 102:625–634. doi: 10.1037/a0019105.
51. Roediger HL, Butler AC. The critical role of retrieval practice in long-term retention. *Trends Cogn Sci* 2011, 15:20–27.
52. Roediger HL, Putnam AL, Smith MA. Ten benefits of testing and their applications to educational practice. In: Mestre JP, Ross BH, eds. *The Psychology of Learning and Motivation: Cognition in Education*, vol 55 . San Diego, CA: Academic Press; 2011,1–36.
53. Carpenter SK, Pashler H, Cepeda NJ. Using tests to enhance 8th grade students' retention of US history facts. *Appl Cogn Psychol* 2009, 23:760–771.
54. McDaniel MA, Agarwal PK, Huelser BJ, McDermott KB, Roediger HL. Test-enhanced learning in a middle school science classroom: the effects of quiz frequency and placement. *J Educ Psychol* 2011, 103:399–414.
55. Leeming FC. The exam-a-day procedure improves performance in psychology classes. *Teach Psychol* 2002, 29:210–212. doi: 10.1207/S15328023TOP2903_06.
56. Lyle KB, Crawford NA. Retrieving essential material at the end of lectures improves performance on statistics exams. *Teach Psychol* 2011, 38:94–97.
57. Carpenter SK, Pashler H. Testing beyond words: using tests to enhance visuospatial map learning. *Psych Bull Rev* 2007, 14:474–478.
58. Karpicke JD, Blunt JR. Retrieval practice produces more learning than elaborative studying with concept mapping. *Science* 2011, 331:772–775. doi: 10.1126/science.1199327.
59. Butler AC. Repeated testing produces superior transfer of learning relative to repeated studying. *J Exp Psychol Learn Mem Cogn* 2010, 36:1118–1133.
60. Rohrer D, Taylor K, Sholar B. Tests enhance the transfer of learning. *J Exp Psychol Learn Mem Cogn* 2010, 36:233–239.

61. Linn MC, Chang H– Y, Chiu JL, Zhang H, McElhaney K. Can desirable difficulties overcome deceptive clarity in scientific visualizations? In: Benjamin A, ed. *Successful Remembering and Successful Forgetting a Festschrift in Honor of Robert A Bjork*. New York: Routledge; 2010,239–262.
62. Pyc MA, Rawson KA. Costs and benefits of dropout schedules of test-restudy practice: implications for student learning. *Appl Cogn Psychol* 2011, 25:87–95. doi: 10.1002/acp.1646.
63. Richland LE, Kornell N, Kao LS. The pretesting effect: do unsuccessful retrieval attempts enhance learning? *J Exp Psychol Appl* 2009, 15:243–257.
64. Butler AC, Roediger HL. Feedback enhances the positive effects and reduces the negative effects of multiple-choice testing. *Mem Cogn* 2008, 36:604–616.
65. Bulgren JA, Marquis JG, Lenz BK, Deshler DD, Schumaker JB. The effectiveness of a question-exploration routine for enhancing the content learning of secondary students. *J Educ Psychol* 2011,103:578–593. doi: 10.1037/a0023930.
66. Gholson B, Witherspoon A, Morgan B, Brittingham J, Coles R, Graesser AC, Sullins J, Craig SD. Exploring the deep-level reasoning questions effect during vicarious learning among eighth to eleventh graders in the domains of computer literacy and Newtonian physics. *Instr Sci* 2009, 37:487–493.
67. Campbell J, Mayer RE. Questioning as an instructional method: does it affect learning from lectures? *Appl Cogn Psychol* 2009, 23:747–759.
68. Jairam D, Kiewra KA. Helping students soar to success on computers: an investigation of the SOAR study method for computer-based learning. *J Educ Psychol* 2010, 102:601–614.
69. Lin HF. Facilitating learning from animated instruction: effectiveness of questions and feedback as attention-directing strategies. *Educ Technol Soc* 2011, 14:31–42.
70. Mayer RE, Stull A, DeLeeuw K, Almeroth K, Bimber B, Chun D, Bulger M, Campbell J, Knight J, Zhang H. Clickers in college classrooms: fostering learning with questioning methods in large lecture classes. *Contemp Educ Psychol* 2009, 34:51–57.
71. Rhodes MG, Tauber SK. The influence of delaying judgments of learning (JOLs) on metacognitive accuracy: a meta-analytic review. *Psychol Bull* 2011, 137:131–148.
72. Dunlosky J, Rawson KA, Middleton EL. What constrains the accuracy of metacomprehension judgments? Testing the transfer-appropriate-monitoring and accessibility hypotheses. *J Mem Lang* 2005, 52:551–565. doi: 10.1016/j.jml.2005.01.011.
73. Finn B, Metcalfe J. Scaffolding feedback to maximize long-term error correction. *Mem Cogn* 2010, 38:951–961.
74. Dina F, Efklides A. Student profiles of achievement goals goal instructions and external feedback: their effect on mathematical task performance and affect. *Eur J Educ Psych* 2009, 2:235–262.
75. McNamara DS, Levinstein IB, Boonthum C. iSTART: interactive strategy trainer for active reading and thinking. *Behav Res Meth Instrum Comput* 2004, 36:222–233.
76. Roy M, Chi MTH. Self-explanation in a multi-media context. In: Mayer R, ed. *Cambridge Handbook of Multimedia Learning*. New York: Cambridge University Press; 2005,271–286.
77. Chi M, Bassok M, Lewis M, Reimann P, Glaser R. Self-explanations: how students study and use examples in learning to solve problems. *Cogn Sci* 1989, 13:145–182.
78. Renkl A. Learning from worked-out examples: a study on individual differences. *Cogn Sci* 1997, 21:1–29.
79. Ainsworth S, Loizou AT. The effects of self-explaining when learning with text or diagrams. *Cogn Sci* 2003, 27:669–681.
80. Chi MH, deLeeuw N, Chiu M, LaVancher C. Eliciting self-explanations improves understanding. *Cogn Sci* 1994, 18:439–477.
81. Kastens KA, Liben LS. Eliciting self-explanations improves children's performance on a field-based map skills task. *Cogn Instr* 2007, 25:45–74.
82. Kuhn D, Katz J. Are self-explanations always beneficial? *J Exp Child Psychol* 2009, 103:386–394.
83. Ozuru Y, Briner S, Best R, McNamara DS. Contributions of self-explanation to comprehension of high- and low-cohesion texts. *Discourse Process* 2010, 47:641–667. doi: 10.1080/01638531003628809.
84. Berthold K, Eysink THS, Renkl A. Assisting self-explanation prompts are more effective than open prompts when learning with multiple representations. *Instr Sci* 2009, 37:345–363. doi: 10.1007/s11251-008-9051-z.
85. Siegler RS, Lin X. Self-explanations promote children's learning. In: Waters HS, Schneider W, eds. *Metacognition Strategy Use and Instruction*. New York: Guilford Publications; 2009,85–113.
86. Matthews P, Rittle-Johnson B. In pursuit of knowledge: comparing self-explanations concepts and procedures as pedagogical tools. *J Exp Child Psychol* 2009, 104:1–21.
87. Hausmann RGM, Nokes TJ, VanLehn K, van de Sande B. Collaborative dialog while studying worked-out examples. In: Dimitrova V, Mizoguchi R, Du Boulay B, Graesser AC, eds. *Artificial Intelligence in Education*. Amsterdam Netherlands: IOS Press; 2009,596–598.
88. Williams JJ, Lombrozo T. The role of explanation in discovery and generalization: evidence from category learning. *Cogn Sci* 2010, 34:776–806.

89. Berthold K, Röder H, Knörzer D, Kessler W, Renkl A. The double-edged effects of explanation prompts. *Comput Hum Behav* 2011, 27:69–75.
90. De Koning BB, Tabbers HK, Rikers RMJP, Paas F. Improved effectiveness of cueing by self-explanations when learning from a complex animation. *Appl Cogn Psychol* 2011, 25:183–194. doi: 10.1002/acp.1661.
91. Gerjets P, Scheiter K, Catrambone R. Can learning from molar and modular worked examples be enhanced by providing instructional explanations and prompting self-explanations? *Learn Instr* 2006, 16:104–121.
92. Crippen KJ, Biesinger KD, Muis KR, Orgill M. The role of goal orientation and self-efficacy in learning from web-based worked examples. *J Interact Learn Res* 2009, 20:385–403.
93. Strømsø HI, Bråten I. The role of personal epistemology in the self-regulation of internet-based learning. *Metacogn Learn* 2010, 5:91–111.
94. Pekrun R, Goetz T, Daniels LM, Stupinsky RH, Perry RP. Boredom in achievement settings: exploring control–value antecedents and performance outcomes of a neglected emotion. *J Educ Psychol* 2010, 102:531–549.
95. Beckmann N, Beckmann JF, Elliott JG. Self-confidence and performance goal orientation interactively predict performance in a reasoning test with accuracy feedback. *Learn Individ Differ* 2009, 19:277–282.
96. Cole JS, Bergin DA, Whittaker TA. Predicting student achievement for low stakes tests with effort and task value. *Contemp Educ Psychol* 2008, 33:609–624.
97. Soenens B, Sierens E, Vansteenkiste M, Dochy F, Goossens L. Psychologically controlling teaching: examining outcomes antecedents and mediators. *J Educ Psychol* 2012, 104:108–120.
98. Brunner M, Artelt C, Krauss S, Baumert J. Coaching for the PISA test. *Learn Instr* 2007, 17:111–122.
99. Byrnes JP. *Cognitive Development and Learning in Instructional Contexts*. 3rd ed. Needham Heights, MA: Allyn & Bacon; 2008.
100. Rittle-Johnson B, Siegler RS, Alibali MW. Developing conceptual understanding and procedural skill in mathematics: an iterative process. *J Educ Psychol* 2001, 93:346–362.